The distribution of some periglacial landforms in Northern Quebec (Canada) as related to climate : An information system approach.

by

Veronique Dewez *

Daniel Lagarec *

Michel Phipps *

* Department of Geography, University of Ottawa

Ottawa, Ont. Canada, K1N-6N5.

ABSTRACT

The spatial distribution of various periglacial and associated landforms in Northern Quebec has been studied using a systemic approach. This study shows that the spatial distribution is very well accounted for by a set of climatic characteristics.

In contrast to the traditional approach whereby the spatial distribution of a particular landform is related to one or two climatic characteristics, the approach used in this study considers the whole set of landforms vis à vis a set of characteristics describing the climate of this region.

The area is considered as a set of sites defined by 1) a type of landform and 2) a particular state with regard to each climatic characteristic considered. Among these characteristics, the PEGASE procedure selects those which allow the most efficient prediction of the localization of the various landforms in the area. The subdivisions created (subsets of sites called T.S.S.) as established by the procedure express the relationships between the climate and the geomorphological landscape. These relationships are further examined using two complementary techniques: 1) a hierarchical grouping method and 2) a correspondence factor analysis.

It has been shown that the main landform gradient corresponds to a thermal gradient expressed by the 'mean annual minimum temperature'. The mineral cryogenic mounds zone displays the coldest conditions all year long; the palsas zone is characterized by cool summers whereas the string bogs zones correspond to more continental conditions with abundant snowfalls. Between the two latters, the palsa-pools zone displays warmer summer temperature than the palsas zone and lesser snowfalls than the string bogs zone.

RESUME

L'étude de la distribution de différents types de formes périglaciaires (palses, buttes cryogènes minérales) ou associées (tourbières réticulées) à l'aide d'une approche systémique montre que cette distribution peut s'expliquer en grande partie par des facteurs climatiques dans la région du Nouveau Québec.

A la différence de ce que l'on trouve généralement dans la littérature, où un type de forme est mis en relation avec des paramètres climatiques pris individuellement, cette étude considère l'ensemble des formes vis à vis du climat.

La région est considérée comme un ensemble de sites définis 1) par un type de forme et 2) par un état donné pour chacune des 21 caractéristiques climatiques considérées. La procédure PEGASE permet de sélectionner, pas à pas, celles de ces caractéristiques qui permettent la meilleure discrimination dans l'espace des différentes formes. Les subdivisions du territoire (ensemble de sites dits T.S.S.) ainsi définies constituent l'expression des relations existant entre les formes et le climat. Ces relations sont examinées de manière plus approfondie grâce à la mise en oeuvre de deux techniques complémentaires: une méthode de groupement hiérarchique et une analyse factorielle des correspondances.

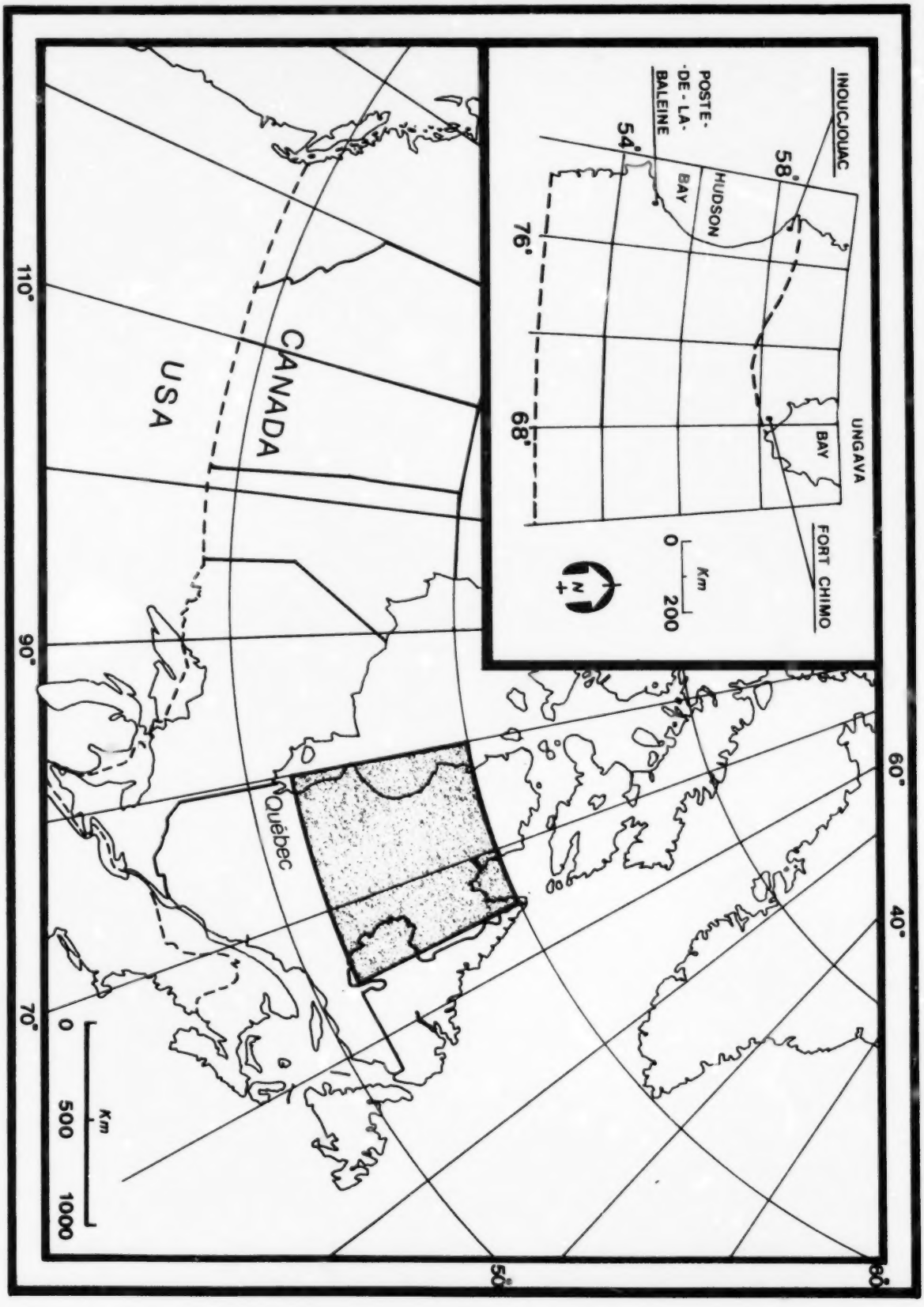
On constate que la gradation des formes correspond à un gradient thermique s'exprimant par la température annuelle moyenne minimale. La zone des buttes cryogènes minérales connait les conditions les plus froides pour l'ensemble de l'année; les palses sont définies par des étés frais alors que les tourbières réticulées connaissent un climat plus continental avec des chutes de neige abondantes. Entre ces deux dernières, la zone caractérisée par des mares de palses a des étés plus chauds que celle des palses et des hivers plus secs que celle des tourbières réticulées.

INTRODUCTION

For many years, various authors have attempted to relate specific climatological characteristics to the spatial distribution of periglacial landforms such as palsas (Åhman, 1977; Dionne, 1978; Lagarec, 1980) or string bogs (Knollenberg, 1964; Ruuhijärvi, 1966; Forsgren, 1969; Thom, 1972). Their approach consisted in comparing, in a given area, the pattern of one type of landform (e.g. palsas) with particular climatic characteristics so as to circumscribe the spatial distribution of this landform within precise climatic boundaries (e.g. isotherms, isohyets, etc). This, however, entailed serious methodological drawbacks since climate and landforms are related through a complex network of links implying more than one or two characteristics. Moreover, the areal distribution of two or more landforms may overlap considerably. An alternative approach which considers the complex intricacies of the geomorphological landscape is, therefore, called for. Given the complex links involved, such an attempt should find its place in the realm of systems analysis, all the more so since we may consider both distributions - landforms and climate - as two spatially organized physical systems, related through partially redundant information (Atlan, 1974).

In this paper, we shall demonstrate how a systems approach based on information theory may be used to determine and analyse quantitatively the relationships between the regional distribution

Figure 1. Localisation of study area



of periglacial landforms observed in Northern Quebec (Figure 1) and a set of characteristics describing the multiple aspects of the climate in this region.

The use of a systems approach in physical and environmental geography has been explored (Leopold & Langbein, 1962) and, more recently, extensively reviewed by several authors (Chorley & Kennedy, 1971; Bennett & Chorley, 1978; Strahler, 1980; Wilson, 1981). In most instances, systems are viewed as 'integrated' ones with a relatively small number of elements interacting through measurable mass, energy and information flows. Their behaviour is generally understood in terms of cybernetics. By contrast, the system to be considered here is of the 'scattered' systems type (François, 1983) and has a great number of elements linked through probabilistic information flows; therefore, it should so be examined from the standpoint of information theory.

This latter theory has been extensively used in ecology for various purposes such as systems modelling (Patten, 1954; Caloux, 1978), diversity studies (Margalef, 1958; Pielou, 1966, 1975), classification procedures (Williams et al., 1966; Orloci, 1978) and the measurement of ecological relationships (Godron, 1968; Guillerm, 1971). Its application to the measurement of characteristics of spatial patterns has been developed by Pielou (1975) and used by Baudry & Burel (1982). It has also served as the basis for a sytematic approach to landscape analysis (Phipps, 1981a, 1981b).

SYSTEM DEFINITION

1. Sampling

The system to be investigated consists of a collection of 'punctiform geographical elements' or 'sites' characterized by i) the landforms which occur and ii) the climatic conditions prevailing in each particular site. The systems analysis will seek to point out the relationships between landforms and climate which exist within the set of sites The set of sites was obtained by systematically covering the study area with an even centered sampling network (grid) based on meridians and parallels. Although the procedure to be used would normally require a large sample (a thousand sites), map-scale and climatic-station considerations limited the sample to 288 sites, approximately 40 km apart.

2. Climatic information

Nineteen climatic characteristics were chosen from the 'Climatic Atlas' (1971) and the 'Atlas climatologique du Quebec' (1978). They included annual, seasonal and monthly characteristics, the latter being chosen at three-month intervals. The characteristics most frequently put forward by various authors to delimit the distribution of cryogenic mounds and string bogs were also included. The climatic data base consisted of twelve temperature and seven precipitation characteristics, to which data on vegetation and altitude were added (Table I). All characteristics

TABLE I

V A R I A B L E S	CODE	UNITS	C L A S S E S
mean annual temperature	AT	C	AT1:-7.5 -5 / AT2:-5 -2.5
annual mean maximum temp.	MA	C	MA1:-5 0 / * / MA3:0 2.5
annual mean minimum temp.	MI	C	MI1:-12.5 -10 / MI2:-10 -7.5
annual mean amplitude	AA	C	AA1:30 35 / AA2:35 40
mean duration of winter	DW	days	DW1:240 220 / DW2:220 200 / DW3:200 180
mean annual growing days	GD	days	GD1:600 800 / GD2:800 1000 / GD3:1000 1200 / GD4:1200 1400
mean duration growing season	GS	days	GS1:80 100 / GS2:100 120 / GS3:120 140
length frostfree period	LF	days	LF1:20 40 / LF2:40 60 / LF3:60 80 / LF4:80 100
mean temp. for march	TM	C	TM1:-22.5 -17.5 / * / TM3:-17.5 -15 / TM4:-15 -12.5
mean temp. for june	TJ	C	TJ1:2.5 5 / TJ2:5 7.5 / TJ3:7.5 10
mean temp. for september	TS	C	TS1:2.5 5 / TS2:5 7.5 / TS3:7.5 10
mean temp. for december	TD	C	TD1:-20 -17.5 / TD2:-17.5 -15 / TD3:-15 -12.5
mean annual precipitation	AP	mm	AP1:300 500 / * / AP3:500 600 / AP4:600 700 / AP5:700 800 / AP6: 800**
mean annual snowfall	SF	cm	SF1:100 200 / * / SF3:200 250 / SF4:250 300 / SF5: 300**
mean precip. for may - sept.	PE	mm	PE1:200 300 / PE2:300 400 / PE3:400 500
mean precip. for march	PM	mm	PM1:0 12.5 / PM2:12.5 25 / PM3:25 37.5 / PM4:37.5 50 / PM5: 50**
mean precip. for june	PJ	mm	PJ1:25 37.7 / PJ2:37.5 50 / PJ3:50 62.5 / PJ4:62.5 75 / PJ5:75 87.5 / PJ6: 87.5**
mean precip. for september	PS	mm	PS1:50 62.5 / PS2:62.5 75 / PS3:75 87.5 / PS4: 87.5**
mean precip. for december	PD	mm	PD1:12.5 25 / PD2:25 37.5 / PD3:37.5 50 / PD4:50 62.5 / PD5: 62.5**
vegetation	VG	/	VG1:toundra / VG2:forest-toundra / VG3:boreal forest
altitude	AL	m	AL1:0 305 / AL2:305 610 / AL3:610 914

* : those initial classes have been reprouped with their immediately preceding class by the procedure because they were considered as not significantly different.

** : those terminal classes regroup 2 or 3 classes because they were individually not statistically significant.

were divided into discrete classes (or states) as shown in Table 1, each site being defined by a particular state of each characteristic.

3. Geomorphological information

The geomorphological data base was taken from the unpublished map of Lagarec (1980), which shows the distribution of four kinds of landforms in Northern Quebec (Figure 2): mineral cryogenic mounds - palsas - pools resulting from palsa decay - string bogs, defined respectively as follows:

3.1.Mineral cryogenic mounds and palsas:

According to Åhman (1977), "a palsa is a hillock or a more elongated rise in the ground, landformed by the build-up of segragated ice in soil, minerogenic or peat or in combination" (p.145). For Seppälä (1982), however, "Palsas are ice-cored peat hummocks which can have a frozen mineral core and rise above the surface of peat bogs." (p.36). The pure mineral mounds of Åhman are thus excluded from Seppälä's definition, even if the mechanism of formation is similar. We will opt for the second definition for palsas, and adopt the term of 'mineral cryogenic mound' for the peatless hummocks, since the insulating role of peat is known to extend the limit of discontinuous permafrost.

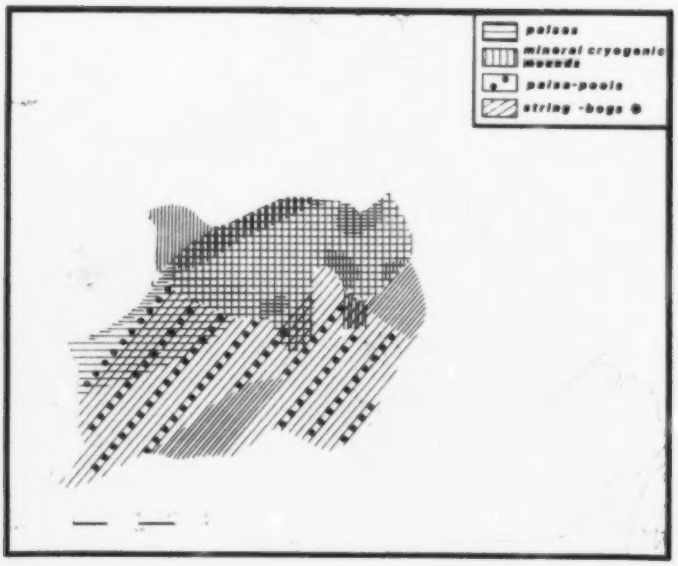


Figure 2. Distribution of cryogenic mounds and string bogs in Northern Quebec.

* the density of lines is indicative of the density of landforms

3.2.Pools:

The degradation of palsas by thermokarst processes gives birth to ponds often surrounded with a rim (Salmi,1973; Seppälä,1982). Under certain circumstances, the water basin will contribute to erode the peat blanket and give birth to string bogs (Lagarec,1982). These features, also mentionned by Dionne (1978), must be distinguished from the large string bogs that have no known genetic link with palsas.

3.3.String bogs:

According to Washburn : "String bogs are muskeg areas characterized by ridges of peat and vegetation, interspersed with depressions that often contain shallow ponds". The author further states: "The origin of string bogs is still not yet establised and a number of hypotheses exist. They are commonly regarded as characteristic of the subarctic taiga." (p.174)

From Lagarec's map, based on extensive photo-interpretation, seven Geomorphological Landscape Units (GLU) can be defined (Figure 3), resulting from the combination of one, two or three of the above-defined landforms (Table II). Each site of the system was defined by a state corresponding to the geomorphological unit to which it belongs.

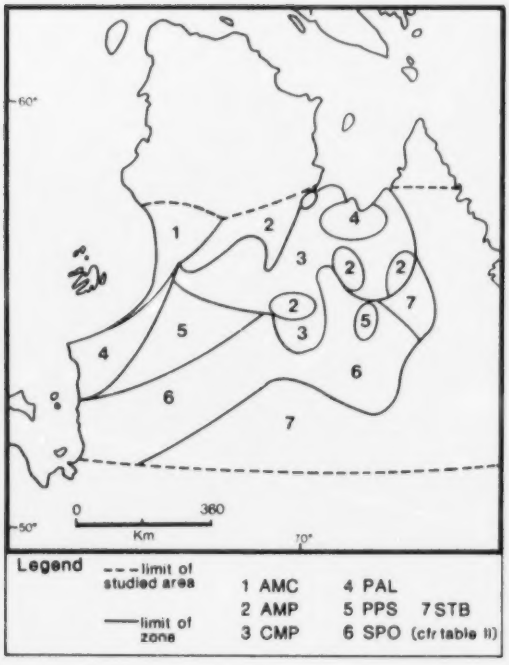


Figure 3. Distribution of the seven geomorphological units.

METHODOLOGY

1. The Pegase procedure :

This procedure has been extensively described by Phipps (1981a) and applied to the analysis of various landscapes (Allaire et al., 1973; Phipps, 1982; Phipps & Dumanski, 1983). The following description will focus on the few points that are essential to the understanding of this study.

Practically speaking, it may be seen as an attempt to construct a new map, as similar as possible to the map of geomorphological landscape units (Figure 3), by using only climatic characteristics combined in a particular order which is to be determined.

Considering the spatial system of the CLU defined above, a guess of the CLU associated with any specific site represents a certain amount of 'uncertainty' in the absence of climatic information. For the whole system, the average uncertainty is measured by the entropy :

$$H = -\sum_{i=1}^{n} p_i \; \mathrm{Log}_e \; p_i \qquad (1)$$

where n is the number of CLU and p_i the probability of occurrence of the ith CLU in the collection of sites making up the system.

TABLE II

GEOMORPHOLOGICAL UNITS

Zone	1	ACM	Abundant mineral Cryogenic Mounds
	2	AMP	Abundant mineral cryogenic Mounds - Palsas abundant palsas - mineral cryogenic mounds
	3	CMP	mineral Cryogenic Mounds and Palsas
	4	PAL	PALsas
	5	PPS	Palsas, Pools and String bogs
	6	SPO	String bogs and POols
	7	STB	STring Bogs

Should landforms and climate be related through some kind of process - e.g. our basic hypothesis - the same guess would eventually entail less uncertainty if it were made with some knowledge of climate. The amount by which the entropy is reduced by knowing a particular climatic characteristic is calculated as a 'mutual information' and has the meaning of a negentropy (Phipps, 1981a). Two further points are important to an understanding of the procedure, although they may be somehow obvious : i) As before, no single characteristic can account for the spatial distribution of the GLU; the pattern shown in Figure 3 is produced by the complex interplay of different aspects of the climate and ii) all characteristics do not provide the same amount of negentropy : some have a higher value than others, they are better predictors of the GLU or, in other words, they play a more important role in the spatial organization of the system under investigation.

The procedure will consist, therefore, in a stepwise subdivision of the initial sample into subsets of sites, on the basis of particular climatic characteristics, as shown in the dendrogram of in Figure 4. At each step, the characteristic which provides the largest amount of negentropy is selected to operate the subdivision. This insures the most rapid decrease of the uncertainty concerning the occurrence of the GLU within the subsets formed as the procedure runs. Because the maximum negentropy criterion favours characteristics with many classes and, therefore, tends to create an overly complex structure, an alternative criterion (e.g. the significance ratio) was prefered here. Like the

former, this criterion aims at achieving the maximum negentropy in the overall process, but it minimizes the number of subsets formed and, thus, tends to bring out the simplest structure of the sample.

In practice, the procedure develops as follows :

1) In the first step all characteristics are tested against the CLU distribution in the initial set of sites; the one with the highest significance ratio is selected and the initial set is subdivided according to the classes of this characteristic.

2) In all subsequent steps, the same procedure applies independently to each subset formed before; the procedure so continues, a subset formed at any step being considered an initial independent group in the following step (see Figure 4).

3) The procedure stops whenever one of 3 conditions is met : i) a subset has less sites than the minimum (20) required to operate the statistical test involved or, ii) the entropy of the subset is lower than a level specified by the operator as the precision level to be reached (0.30) or, iii) a subset contains enough sites, and its entropy is still above the precision level, but none of the available characteristic provides significant negentropy.

The end product of the procedure is a number of Terminal Sub Sets (TSS) that could not be further divided. Each TSS represents: i) a

set of sites and , therefore, a choric division of the area (Figure 6); ii) a specific combination of climatic variables (i.e. a branch of the dendrogram), thus representing particular environmental conditions relevant to the spatial variation of the GLU; and iii) a specific probability vector with regard to the occurrence of these GLU (Table III).

In summary, the TSS, with their spatial location, their environmental conditions and their geomorphological content, constitute the links between climate and landforms.

2. Grouping technique :

Although two TSS correspond to different environments, they may yield similar results with respect to the occurrence of the geomorphological units. They constitute groups of TSS which can be established using a grouping technique. This was done by means of an agglomerative, hierarchical and polythetic method (Spence & Taylor, 1970) based on minimum information loss (Dale & Andersen, 1970; Beguin, 1979; Legendre & Legendre, 1979).

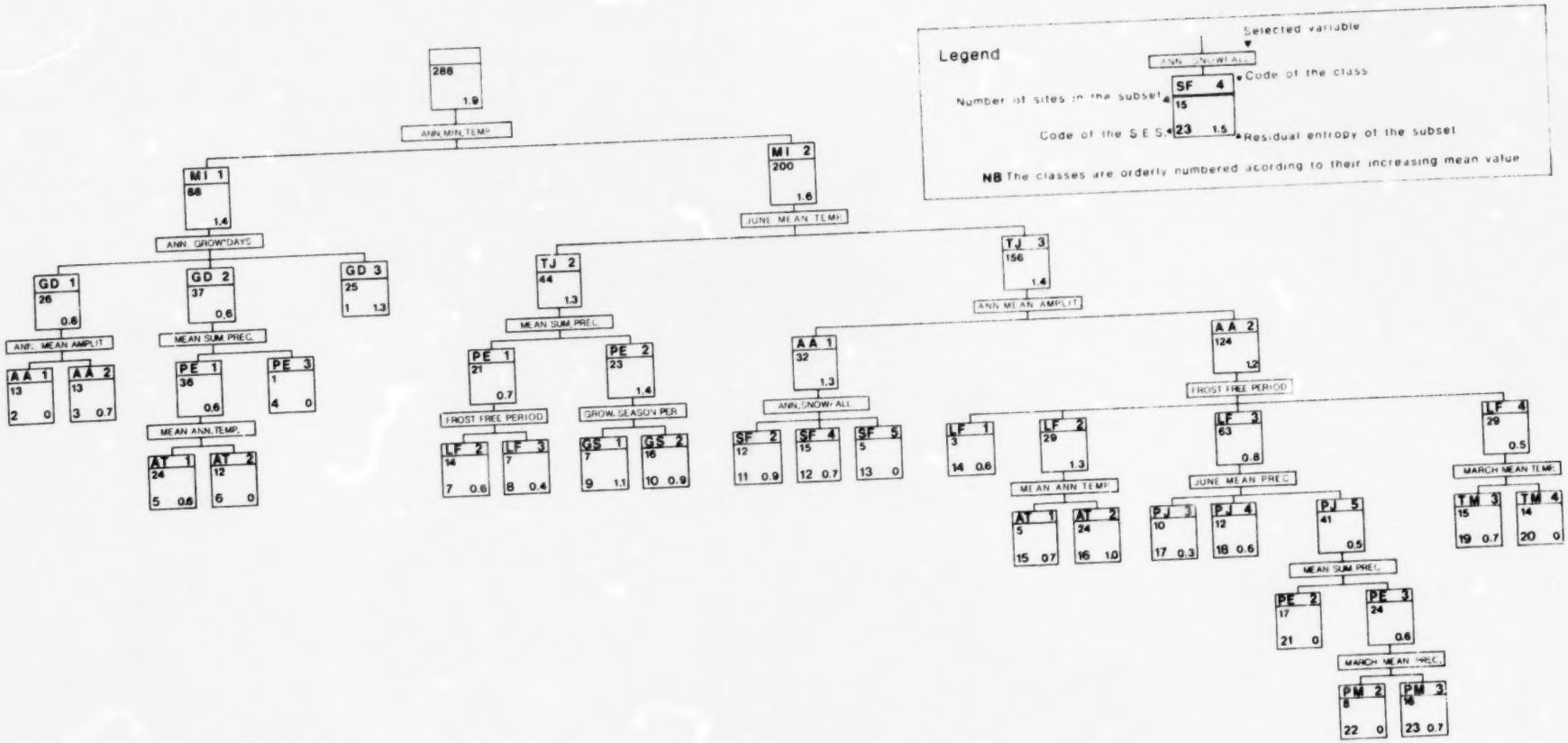
The results are depicted by: i) the curve of the information loss as a function of the successive groupings (Figure 7) and ii) the dendrogram showing the cluster hierarchy (Figure 8). Both graphs allow the determination of the classification level to be adopted. These groups are further defined by the probability of occurrence of the landforms (Table III) and may be subsequently mapped also (Figure 6).

3. The correspondence analysis:

The Pegase and the grouping procedures respectively give a set of TSS and TSS groups individualized on the basis of climatic variables, and characterized by the probability of occurrence of the QLU. The fundamental climate/landform relationships may be further examined by performing a correspondence factor analysis on the probability matrix displayed in Table III (Beguin, 1979; Legendre & Legendre, 1979). This technique has an objective similar to that of principal component analysis, i.e. the generation of a few orthogonal non-redundant factors providing the best description of the relationships included in the data matrix (Beguin, 1979). However, since it is based on the CHI-square distance it is specially designed to handle frequency or probability data.

This analysis will show the structural linkage between TSS and the QLU through their proximity in the factor space: a close proximity between a particular TSS and a specific QLU will express the importance of the QLU in this TSS; along the same lines, a close proximity between two TSS will betray a resemblance as to the QLU they contain and, conversely, a close proximity between two QLU will express the fact that both tend to occur similarly throughout the set of TSS. A major advantage of the correspondence analysis over other types of factor-analytic methods is the capability to represent, in the same factor space, both the spatial entities (here the TSS) and the characteristics observed (here the QLU).

Figure 4. Dendrogram resulting from the PEGASE procedure.



Both are represented in the factor planes, as shown in Figure 9. The first interpretation suggested a rotation, in order to better adjust, in the multi-variate space, the group of factors with the clusters of TSS and geomorphological units. This has been done using a few elementary mathematical operations in order to clarify the interpretation of the factors.

RESULTS

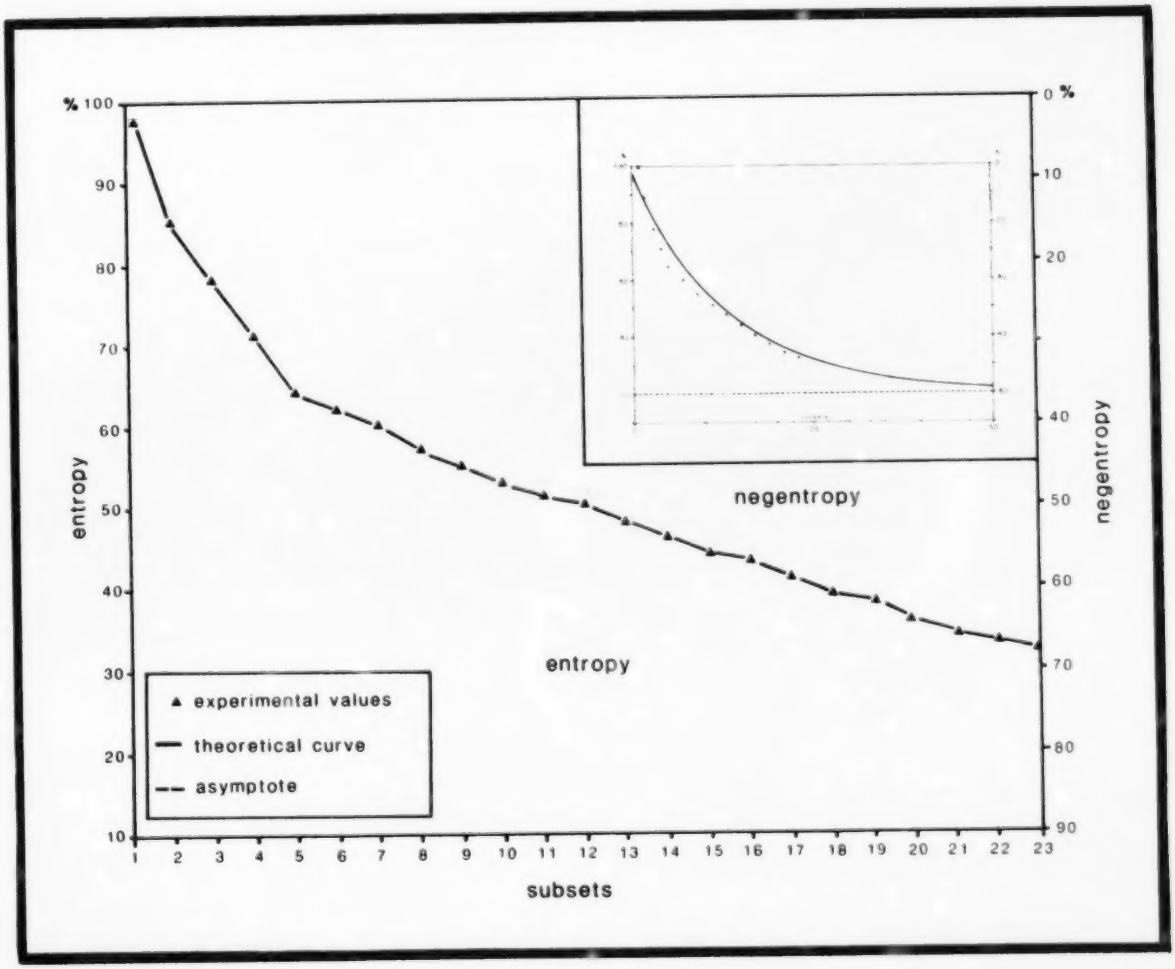
1.The Pegase procedure:

The procedure was applied to the data set using the significance ratio (SR) as the selection test. The following results were obtained: in seven steps, the divisive procedure gave 23 TSS, with a residual entropy of 0.60, 32% of the initial value, thus representing a negentropy (level of order) of 68%. Twelve variables were selected out of a total of 21 : 8 temperature and 4 precipitation characteristics.

1.1 The negentropy gain:

We shall first examine the question of residual entropy from a theoretical point of view. Figure 5 shows intermediate values between the initial and final values of the entropy. This experimental curve may be fitted to the following negative exponential function:

Figure 5. Decrease of entropy as a function of the number of subsets



$$\frac{Hn}{Hl} = 0.722\, e^{-0.075\, n} + 0.20$$

where Hl is the initial entropy, and Hn the entropy corresponding to the n subsets.

The asymptotical value 0.20 thus represents an estimate of the residual relative entropy, should the divisive procedure be pursued with no limitation (Phipps, 1981a). The expected level of negentroy in the system reaches the high value of 80%, supporting the conclusion that the geomorphological system investigated at this particular scale is highly organized with respect to climatic characteristics. This enables us to further examine the climate/landforms relationships.

1.2 The hierarchical division:

The dendrogram (Figure 4) synthesizes the divisive procedure. All the TSS are defined and individualized by a hierarchic arrangement of climatic variables that can be analyzed. The probability matrix displayed in Table III shows how these sets differ from each other as to the CLU they contain.

The 'annual mean minimum temperature' was the most discriminant for the system as a whole and was selected first to divide the area. It distinguishes zones where the minimum temperature is less than -10° C (M11) from zones where it is higher than this value (M12).

At the second step, the area is divided into 5 subsets: two result from the subdivision of MI1 according to the 'mean number of growing-degree-days'and the three others result from the subdivision of MI2 according to 'June mean temperature'. The first subset, MI1-GD1, (which will further produce TSS 2-3) is characterized by GLU displaying mineral cryogenic mounds (ACM); the second, MI1-GD2, (i.e. the TSS 5-6) by the dominance of CMP unit (mineral cryogenic mounds - palsas); the third one MI1 - GD3 (i.e. the TSS 1) by the co-occurrence of various GLU; the fourth one MI2-TJ2 (i.e. the TSS 7-8-9-10) GLU with palsas (PAL) and the last one MI2-TJ3 (i.e. the TSS 11 to 23) by GLU with pools and string bogs resulting from palsa decay (PMT) and/or with abundant large string bogs (SPO - STB).

Except for TSS 1 which could not be further determined due to the lack of discriminant characteristics, the other subsets already show a relatively low level of entropy.

The next steps further specify the climatic constraints acting upon the localisation of the various GLU: (1) the prominent part played by the factor "cold" in the distribution of mineral cryogenic mounds versus palsas is re-emphasized by various characteristics that individualize TSS 2 from 3, 5 from 6, 7 from 8 and 9 from 10: low annual mean amplitude, low mean annual temperature, short frost free period and short growing season all correspond to higher frequencies of GLU with mineral cryogenic mounds; (2) mineral cryogenic mounds seem not to depend on precipitations (TSS 2-3),

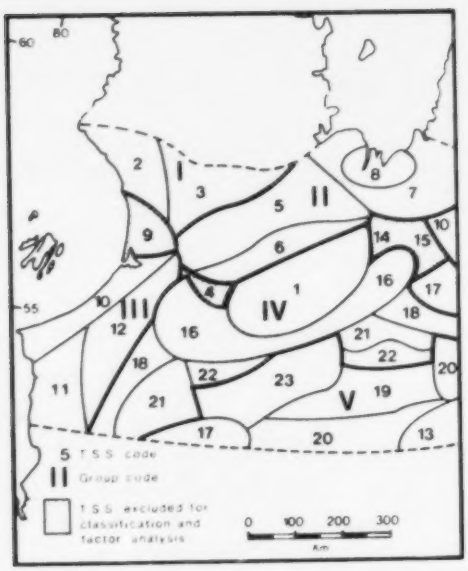


Figure 6. Localisation of the T.S.S. and T.S.S. groups.

whereas the presence of palsas is more related to summer precipitations (TSS 7 to 10). String bogs (TSS 17 to 23) seem to be strongly dependent on annual and monthly snowfalls as well as summer precipitations; (3) string bogs are specifically characterized by high annual mean amplitudes, a long frost free period and abundant precipitations.

A systematic description of the dendrogram would quickly become tedious. The results achieved by the clustering technique and the correspondence analysis will actually clarify the structural relationships between the climatic TSS and the landforms.

In summary, for the whole system, it may be stated that (1) temperatures play a more general role than precipitations, (2) mineral cryogenic mounds require cold minimal temperatures all year long, (3) the most discriminant characteristic for palsas in the studied area is summer coolness (low June temperature), (4) string bogs are centered in the mildest zones.

2.The cluster analysis:

The procedure was applied to 19 TSS, four being discarded because of their small size (less then 10 sites) and high heterogeneity (TSS 4-9-14-15). The information loss along the process is presented in Figure 7. A drastic slope change following the 15th step suggests that this point be chosen as the final level for

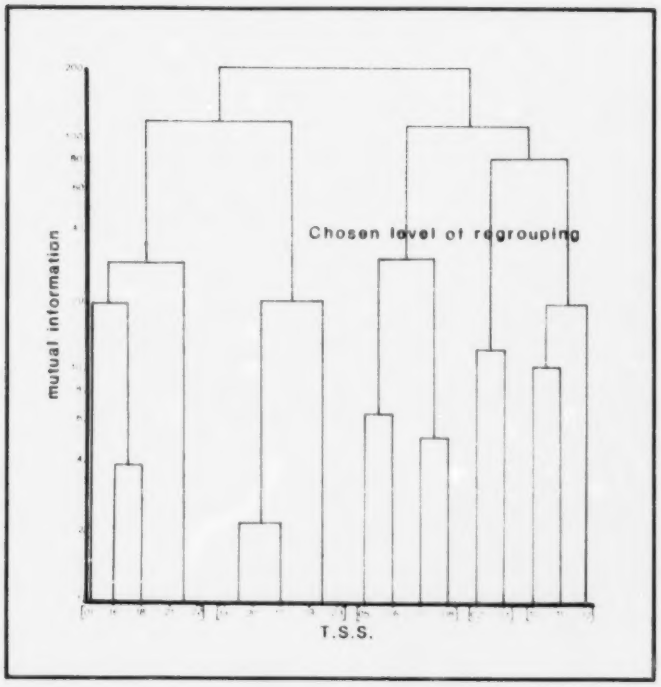


Figure 8. Dendrogram of the cluster hierarchy

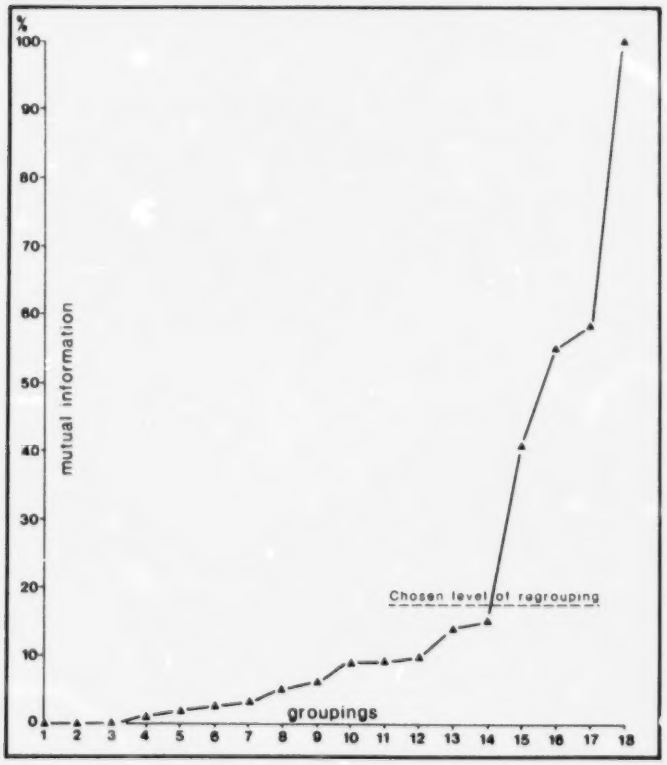


Figure 7. Information loss as a function of the number of groupings

regrouping. Five clusters were thus kept. Figure 8 shows how the TSS are grouped; the map in Figure 6 displays the spatial distribution of the groups, and Table III gives the relationship between these groups and the geomorphological landscape units.

Group I (TSS 2 - 3)

This group is located in the NW part of the area and includes 95% of the sites with mineral cryogenic mounds (ACM).

Group II (TSS 5, 6, 7 and 8)

It forms the NE zone and includes nearly 80% of the sites associated with the GLU 'mineral cryogenic mounds and palsas' (CMP).

Group III (TSS 10, 11 and 12)

This is a maritime area located along the southern part of Hudson Bay. The TSS concerned favor the presence of palsas (PAL) and their degradation into pools and small string bogs (PPS).

Group IV (TSS 1, 16, 18, 21 and 22)

It constitutes a large area in the central and SW parts of the region and is characterized by string bogs combined with some pools (SPO), 70% of this unit being centered there.

Group V (TSS 13, 17, 19, 20 and 23)

This last group forms the southernmost zone of the area and is characterized by a high concentration of sites with string bogs (SIB), as 95% of this unit are located in these TSS.

TABLE III

GROUP	T.S.S.	FORMS (frequencies) ACM	AMP	CMP	PAL	PPS	SPO	STB	FORMS(% of types) ACM	AMP	CMP	PAL	PSS	SPO	STB	FORMS (% of groups) ACM	AMP	CMP	PAL	PSS	SPO	STB
I	02	13							65							100						
	03	6	7						30	35						46	54					
II	05		7	17						35	34						29	71				
	06			12							24							100				
	07			9	5						18	15						64	36			
	08			1	6						2	19						14	86			
III	10	1			11	2		2	5			34	7		5	6			69	12		13
	11				7	1	4					22	3	5					58	9	33	
	12				3	11	1					9	38	1					20	73	7	
IV	01		6	7		2	10			30	14		7	13			24	28		8	40	
	16			4		9	11				8		31	14				16		38	46	
	18					4	8						14	11						33	67	
	21						17							22							100	
	22						8							10							100	
V	13							5							11							100
	17						1	9						1	20						10	90
	19						8	7						10	16						53	47
	20							14							30							100
	23						8	8						11	18						50	50
	04					1																
	09	4	1	1	1																	
	14		2	1																		
	15			3				2														

Group I and V show the greatest homogeneity. They both contain only two GLU, of which one is dominant with a relative frequency above 70% (ACM for I and STB for V). Both are strictly spatially and climatologically opposed, thus suggesting that the climatic constraints are most effective on the distribution of mineral cryogenic mounds and string bogs.

The second group is less homogeneous, since three geomorphological units are present, of which two can be dominant according to the TSS concerned (CMP or PAL), and since the dominance level is less conspicuous.

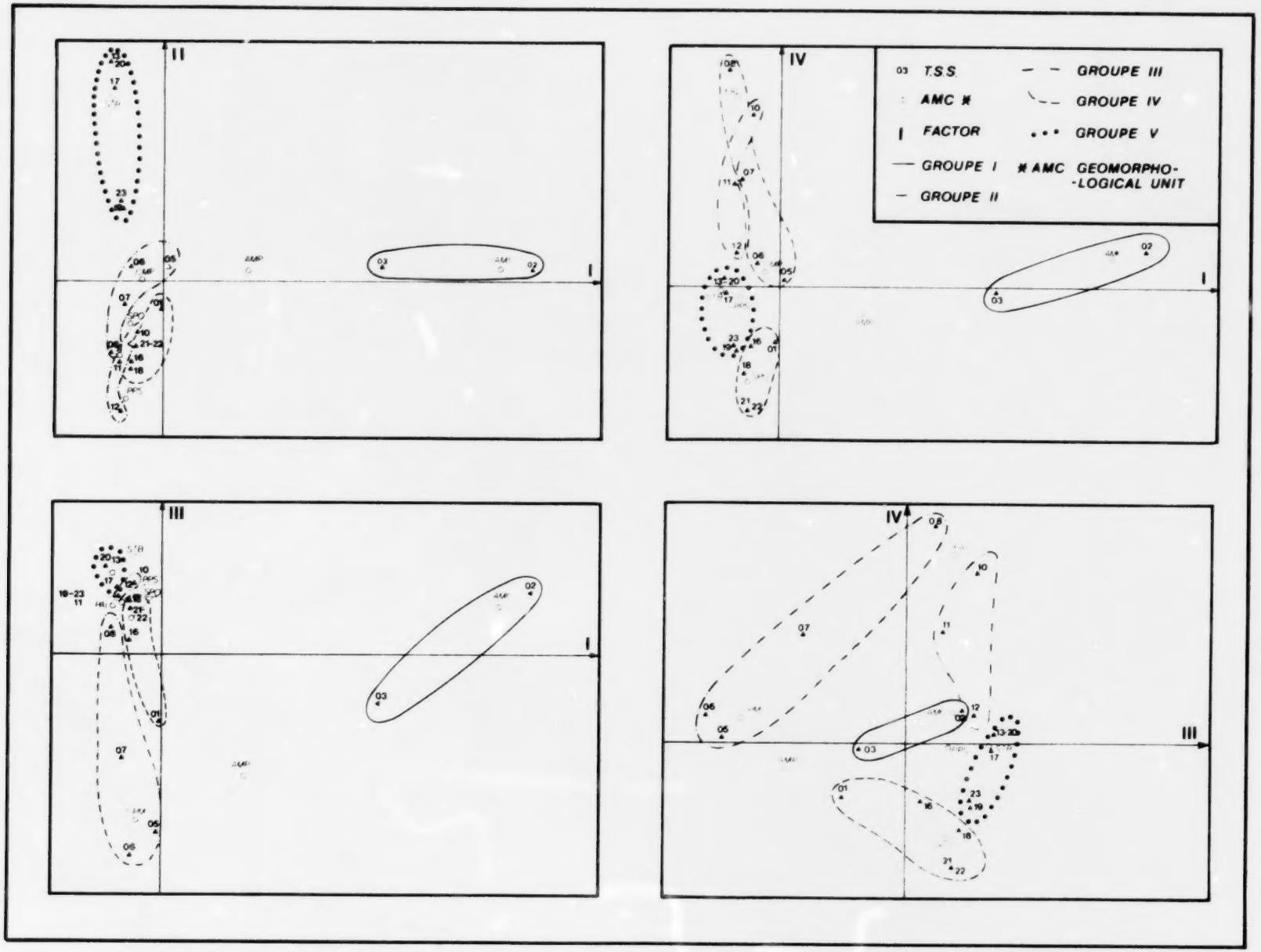
The third and fourth groups are highly heterogeneous, since they are characterized by the co-occurrence of several GLU so that the 4 landforms of the system occur. These groups are thus poorly determined by the climatic characteristics. This might also be deduced from the high residual entropy of some of the TSS it contains -especially TSS 1- (cfr. Figure 4).

This grouping procedure leads to a simplified spatial structure that makes the analysis and interpretation easier.

3.The correspondence analysis:

The procedure was applied to the same matrix as the grouping technique. Four selected factors explained 84.5% of the total

Figure 9 Principal factor planes



variance of the system, respectively 25%, 23%, 18.5% and 17% (after rotation). The interpretation is based i) on the position of the TSS and QLU in the 4 principal factor planes (Figure 9) and ii) on 4 maps of the TSS according to their factor scores (Figure 10).

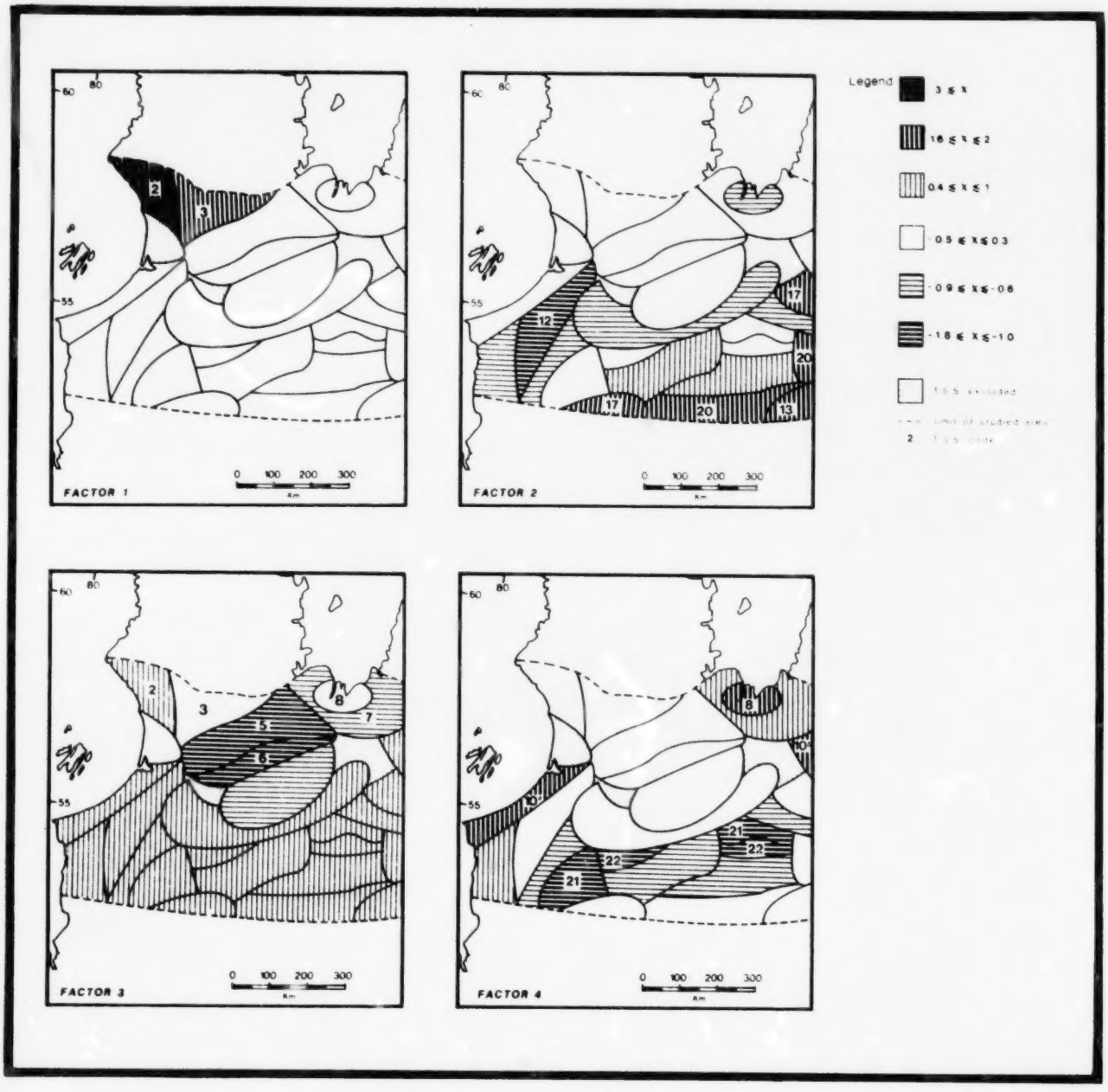
Factor I

It clearly sets Group I (i.e. TSS 2 and 3) over the other TSS as well as the QLU with mineral cryogenic mounds (ACM mainly, AMP to a slighter extent) against the others. From the climatic point of view, the coldest zone (NW) is involved: the annual mean minimum temperature is very low, summers are short and cool, especially in TSS 2 where the cooling influence of Hudson Bay is effective. This factor, thus, represents the influence of 'COLD' . The spatial extent of mineral cryogenic mounds can thus be associated with a climate that is rigorous enough to provide for the formation and/or preservation of ice-cores in a mineral soil with neither peat nor forest protection.

Factor II

It sets TSS 12 against 13, 17 and 20, and unit PPS (palsas, pools and small string bogs) against unit STB (large string bogs). The climatic characteristic involved is snowfall for the January - April period. This variable is low for TSS 12 and high for 13, 17 and 20. The association of string bogs and high snowfall is easily interpreted: string bogs require large amounts of water and the early spring thaw of the ridges. Both conditions are positively related to abundant winter snowfalls: snow melting will supply the

Figure 16. T.S.S. factor scores for the first four factors



water while a thick snow blanket will limit the vertical extent of freezing. On the other hand, the occurrence of palsas and their degradation forms in TSS 12, which is in a relatively meridional position, could be understood as a consequence of weaker snow protection in the winter, promoting deeper freezing and later thawing.

Factor III

It brings out two gradients: the first one opposes TSS 2 to TSS 5 and 6, while the second one opposes TSS 8 to 5 and 6. They set unit CMP (mineral cryogenic mounds and palsas) against ACM (abundant cryogenic mounds), on the one hand, and on the other hand, CMP against PAL. The climatic characteristic concerned is the winter temperature, which is lowest in TSS 5 and 6. The association between rigorous winter temperatures and the distribution of mineral cryogenic mounds - palsas in these two TSS could be explained by the importance of conditions promoting freezing to great depths, thus enabling permafrost to extend in a relatively southern zone, where the summer is relatively warm. The slightly northern localization of TSS 5, as opposed to 6, corresponds to a slightly higher 'mineral cryogenic mounds/palsas' ratio, which is in perfect agreement with our first gradient leading to an abundance of mineral cryogenic mounds in TSS 2, i.e. the annually coldest zone. The gradient leading to the abundance of palsas along Ungava Bay is less obvious, but the analysis of various maps suggested that strong currents and tides in this zone could delay the freezing of the sea, promoting a longer maritime influence in autumn. To this climatic hypothesis, we should add

the 'peat' condition, essential for what we call 'palsas': peat is much more abundant along the coast than inland on the plateau. But since peat growth closely depends on climatic conditions, the difference between the west (Hudson) and east (Ungava) coast has to be at least partially of climatic origin.

Factor IV

It sets the two coastal zones (Hudson and Ungava, TSS 10 and 8), against the inland zone (TSS 21 and 22). In this case, the June mean maximum temperature is involved, being lowest along both coasts, where palsa sites are centered, and rising inland where pools and string bogs are found. The association palsas - cool June temperature, stated already in the dendrogram (Figure 4), is here confirmed. This can easily be understood along the Hudson coast as summer coolness is essential for the preservation of ice-cores at a very low latitude. This condition can be realized along the coast thanks to the cooling influence of the sea water, but with increasing distance from the sea, it drops sharply, limiting permafrost distribution to small spots. Along the coast of Ungava Bay, cool summer temperatures could be seen as the complement of relatively mild winter conditions, promoting the spread of palsas, but being still too clement for mineral cryogenic mounds to be developed.

The factor analysis thus leads to the interpretation of the whole set of TSS and geomorphological landscape units in terms of four non-redundant factors which combine the most discriminant climatic characteristics for the distribution of the landforms (Table IV).

TABLE IV

FACTOR ANALYSIS RESULTS

FACTOR	T.S.S.	TYPES	MEANING
I	2-3	ACM	annual cold
II	12 / 13-17-20	PPS/STB	January-April snowfall
III	5-6 / 2-3 / 7-8	CMP/ACM /PAL	Winter cold
IV	7-8-10-11 / 18-21-22	PAL/SPO	June mean max temp.

DISCUSSION

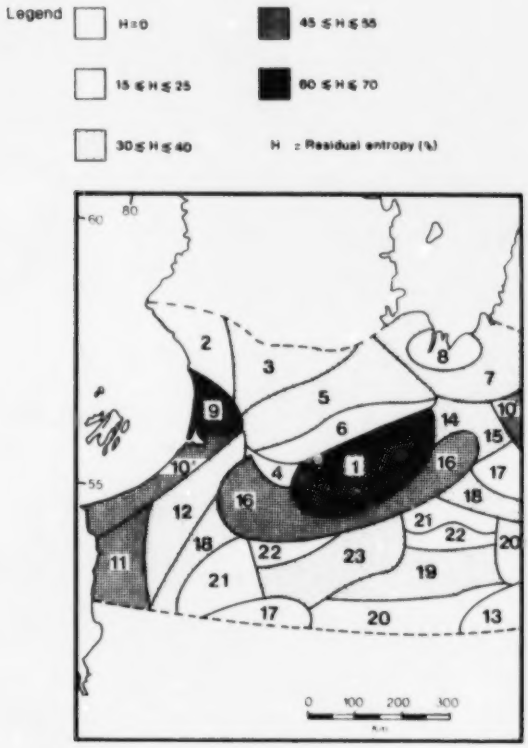
1.Residual entropy

The residual entropy measures the uncertainty left in the system after the formation of the TSS. It actually amounts to 0.60 for the whole area. The contribution of the various TSS, however, is far from being equal as shown in Figure 4. Some TSS may have a low entropy, the landforms occuring there being highly determined. Others have a high residual entropy, signaling zones where the climate/ landforms relationship is weak. The level of residual entropy has been mapped to show how the strength of the climatic contraint varies over the study area (Figure 11).

Low entropy areas tend to occur in the southernmost sections of the region (i.e. TSS 13, 17, 21 and 22) and to a lesser extent, in the northernmost section (TSS 2 and 8). With the exception of TSS 6, the centre of the area and the west coast still have a high entropy while the intermediate zones (i.e. TSS 3, 5, 7, 12, 18, 19 and 23) display intermediate values.

This pattern may be easily understood since the central area constitutes a context of transient influences and weak climatic gradients which probably allow for the mixed occurrence of different G.U. In such conditions, the existing information was

Figure 11. Residual entropy of the 23 T.S.S.



unable to further lessen the uncertainty. This limitation could probably be overcome in two complementary ways : 1) by a refinement of the climatic information and 2) by the addition of new information - especially non-climatic information - to the initial set of characteristics. Both solutions, however, would require changing the scale of the study, implying the reduction of the study area and an increased sampling density. In other words, they would require the definition of a larger scale system uncluding information relevant to the very scale of this system and to which a similar procedure could be applied.

Returning to the present system, the high residual entropy of TSS 9 and 10 can be understood as a problem in the inadequate division of the characteristics concerned: the N -- S and the W -- E gradients between mineral cryogenic mounds and palsas are too steep for the degree of accuracy of the climatic characteristics. As for the other TSS, their residual entropy would have certainly been weaker if the sample had been larger: the procedure stopped there since the number of sites was less than the minimum.

2.The results in relation to the literature

Much has been written about palsas, mineral cryogenic mounds and string bogs. Åhman (1977) provides a review of most of the work dealing with the distribution and/or process of formation of palsas and mineral cryogenic mounds. For string bogs - a landform the

genesis of which is not yet well established (Washburn, 1979) - no recent synthesis exists, although Ruuhijärvi (1966) for Scandinavia, and Allington (1961), Knollenberg (1964) and Thom (1972) for Canada, give an overall appreciation of the problem.

Depending on their objectives, various authors have worked at different scales and, as a consequence, have related the landform in question to different climatic variables. The main characteristics will be reviewed here, going from the most general to the most detailed indices.

Mean annual air temperature and vegetation have been put forward by all authors, since both are available in most areas and are of a general character. Moreover, the mean annual temperature is usually related to the distribution of permafrost, which is essential to the development of palsas. As far as string bogs are concerned, they are often related to the boreal forest. The mean annual precipitation, another variable of a general character, is mentionned by a few authors only.

Seasonal characteristics - temperatures and precipitations - have also been mentioned. Palsas have been often related to (1) a certain length of the annual frost period, (2) short and/or cool summers, (3) thin snowfall and/or snow cover, and, sometimes, to (4) continentality. String bogs are usually related to (1) seasonal frost promoting a deep active layer and involving a

continental climate, (2) short summers, (3) important snowfalls, (4) summer precipitations greater than evaporation, and, finally, (5) to spring melt water inundations.

Another type of characteristics consists of indices taken simultaneously - i.e. the freezing and the thawing indices (Harris, 1982) or the soil temperature as a function of air temperature and snowdepth (Lagarec, 1980).

This short review shows that most studies address one type of landform in relation to a single or, at most, two climatic parameters. It is obvious that such reductionist approach could allow neither for a comparison of the roles of the various characteristics considered, nor for a hierarchization of these roles.

In contrast, the method used in the present paper deals with several types of landforms and a whole set of climatic variables, seen as two interrelated spatial systems, thus providing a better chance to understand the relationships between climate and the distribution of landforms.

A. Mean annual parameters and vegetation:

The mean annual minimum temperature was selected by the procedure as the most prominent feature, clearly outweighting the mean annual maximum temperature and the mean annual average temperature generally considered as the best indicator by most authors. This

may be explained by the fact that minimum temperature reflects winter cold as well as summer coolness which both may play a significant role in the conservation of the ice core of palsas and mineral cryogenic mounds.

The vegetation as defined in this study (Table 1), was not selected at any step of the procedure because of its high correlation with the mean minimum temperature. In the first step, however, the temperature was more effective than vegetation and was, therefore chosen. The non-selection of vegetation in any subsequent step clearly shows that this characteristic does not bring negentropy of its own.

B. Seasonal parameters

The crucial role of 'short and cool summers' is underlined in the second step of the procedure by the selection of the number of growing degree days and June mean temperature: It was shown that the gradient from low to high number of growing degree days was parallelled by a shift from mineral cryogenic mounds to palsas and, finally, to palsas pools and small string bogs. A similar effect was found to occur with June mean temperature since low values of this characteristic were clearly related to abundant palsas, thus confirming the view expressed by Dionne (1978) and Lagarec (1980) that the cooling influence of the Hudson and Ungava Bays is crucial to the maintenance of palsas.

The length of the frost-free period and growing season (complement of the 'length of annual frost period') intervenes as well, but in the fourth step, with a secondary discriminating role.

Snowfall, often considered important to palsas and mineral cryogenic mounds, was found much more crucial for the occurrence of string bogs. This does not mean that palsas are independent of snowfall, but, by looking at the whole system it becomes clear that this parameter is much more effective with regard to string bog distribution than to palsas in Northern Quebec.
The depth of snowcover has not been considered, the data not being available. Furthermore, this parameter seems mainly related to micro-topography and is, threfore, less relevant at the scale of our system than at the scale of a palsa-field for example (Seppälä, 1982).

The annual amplitude was not found to be effective in the distribution of palsas. When it appeared (for mineral cryogenic mounds), its role was negative : the abundance of mineral cryogenic mounds was in inverse relationship to continentality. On the contrary, string bogs were closely and positively related to the annual amplitude (third step), characteristic which distinguished them from thermokarst features. This analysis thus confirms the importance of the annual thermal deviation for string bogs, but does not corroborate Karte's statement (1979) which links the development of palsas and continentality.

The role played by summer precipitations in string bog development, as stated by some authors, was found to be positive but weak, since this parameter was not selected before the sixth step. This limits its role to a small area in the system.

The comparison of these results and those obtained by other methods shows many similarities and some discrepancies. However, it allows above all to underline some advantages of the systems approach. Three points deserve consideration:

Due to the structure of the procedure, characteristics are selected in an order which represents their power of discrimination vis a vis the geomorphological landscape units. This order reflects their importance as conditions necessary to the development of the landforms, at the particular scale of the system being considered. A true hierarchy is thus established among these characteristics which, otherwise, would have to be accorded the same importance.

A second consequence of this structure is the contextual view of the relationships between the climate and the geomorphological landscape. This point may be exemplified in Figure 4. Annual snowfall is a very weak constraint in terms of its action upon the whole system, its negentropy being considerably outranked by most other characteristics. However, in a specific context (defined by the classes MI2-TJ3-AA1) with relatively warm conditions and low

thermal amplitude, this characteristic becomes a constraint of the utmost importance (Figure 4). In such an environmental context, snowfall brings a negentropy which represents as much as 48% of the residual entropy. Moreover, this characteristic is particularly useful since it clearly circumscribes the conditions which allow the development of respectively palsas (SF2) and string bogs (SF5). This example clearly shows that the role of a characteristic as a constraint has to be tested in a particular context.

It should also be stressed that eventhough the techniques implied by this approach are quantitative, the data are used in a purely qualitative way since the values taken by the climatic variables are classified and further treated as state variables. Far from entailing a loss of accuracy as often thought, this type of treatment might fit to the very nature of the problems at hand. The phenomena studied, indeed, abundantly show thresholds and changes of state as a response to the quantitative variation of some stimuli. Emphasis is placed rather onto a more precise assessment of the role played by these climatic variables in the spatial organization of the geomorphological landscape. This is the role of the entropy calculated for each subset formed. Among other advantages, this lessens the importance of the absolute values of climatic variables, thus promoting an easier generalization since these values tend to vary according to the area considered (AHMAN, 1977).

Finally, the very objectives of both types of approaches - traditional and systemic - are in contrast. While traditional approaches attempt to circumscribe the areal distribution of one particular landform, the systemic approach aims at finding out the most efficient discrimination between a set of areal distributions corresponding to the various landforms of a landscape. This systemic approach, since it takes into consideration the relationships between landforms in a given region, seems to be the most appropriate way to really deal with the geomorphological landscape in the manner advocated by St-Onge (1981).

CONCLUSION

A systemic approach applied to the analysis of the geomorphological landscape in Northern Quebec leads to five main conclusions :

Eventhough a small sample was used (less than 300 sites), the study produced significant results : this is vitally important for the study of northern areas where data sources are scattered.

This approach leads to a better interpretation of the distribution of landforms, because 1) each individual landform is considered in relation to the others, and 2) it involves a set of climatic characteristics instead of single ones.

The results confirm those of previous studies, but goes further by providing a hierarchy of the characteristics involved with each geomorphological landscape unit, and by quantifying their 'discriminant power' : these are two major advantages of the method used in this paper.

The independence of the climatic combinations that characterize unequivocally each terminal subset enables the user to interpret the results. The residual entropy of the TSS allows for the localization of zones with a high uncertainty. In these zones, a second analysis - at a larger scale and integrating other characteristics to the initial set - would be desirable.

The Pegase procedure, by dividing the area into climatic subsets that best correspond to the observed distribution of landforms, provides a synthetic view of the landscape not only in ecology (the field for which it had been conceived) but also in geomorphology and climatology. As this paper has shown, a further inspection using a cluster and a factor analysis enables the user to maximize the information drawn from this procedure.

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Note

PEGASE stands for ' Partition d'un Ensemble Géographique pour l'Analyse Spatiale Ecologique '. The procedure has been integrated in a computer routine by Michel Phipps. Information and additional details concerning the programme may be obtained by writing to the author concerned.

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